SUSY Searches at Tevatron Collider

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This article presents recent results of searches for Supersymmetry using the CDF and the DØ detector at the Fermilab Tevatron Collider. Described are the Tevatron searches for third generation scalar quarks and for supersymmetric signatures involving photons. All the reported results have been obtained assuming theoretical models in which $\mathcal{R}$-parity is conserved.

1 Introduction

1.1 Supersymmetry

Although at present, the Standard Model (SM) provides a remarkably successful description of known phenomena, it seems to be, most likely, a low energy effective theory of spin-1/2 matter fermions interacting via spin-1 gauge bosons [1]. An excellent candidate of a new theory, able to describe physics at arbitrarily high energies, is Supersymmetry (SUSY) [2]. SUSY is a larger space-time symmetry, that relates bosons to fermions. Even if we don't have direct experimental evidences of SUSY, there are remarkable theoretical properties that provides ample motivation for its study. SUSY describe electroweak data equally well than SM but, in addition, allows the unification of the gauge couplings constants, the unification of the Yukawa couplings and do not require the incredible fine tuning, endemic to Higgs sector of the SM. Naturally, SUSY cannot be an exact symmetry of the nature, as none of the predicted spin 0 partners of the quarks or leptons and none of the spin 1/2 partners of the gauge bosons have been observed so far [3].

In Supersymmetry fermions can couple to a sfermion and a fermion, violating lepton and/or baryon number. To avoid this problem, a new quantum number, the $\mathcal{R}$-parity, has been introduced [4]. For SM particles $\mathcal{R} = +1$, for the SUSY partners $\mathcal{R} = -1$. $\mathcal{R}$-parity conservation has deep phenomenological consequences [5]. SUSY particles can be only produced in pairs; the lightest supersymmetric particle (LSP) does exist and it is stable and interacts very weakly with the ordinary matter, leading to a robust missing transverse energy signature ($\not\!\!E_{\mathrm{T}}$); the LSP is a natural candidate for the dark matter. In the present article, we present a review of recent Tevatron searches performed assuming $\mathcal{R}$-parity conservation.

1.2 Gauge Mediated SUSY Breaking Models

Theories with gauge-mediated supersymmetry breaking (GMSB) provide an interesting alternative scenario. In GMSB [6,7], the dynamical supersymmetry breaking (DSB) is mediated by gauge interactions. In recent years, many mechanism for DSB have been found and realistic models have been constructed. This class of models assumes that supersymmetry is broken with a scale $\sqrt{F}$ in a sector of the theory

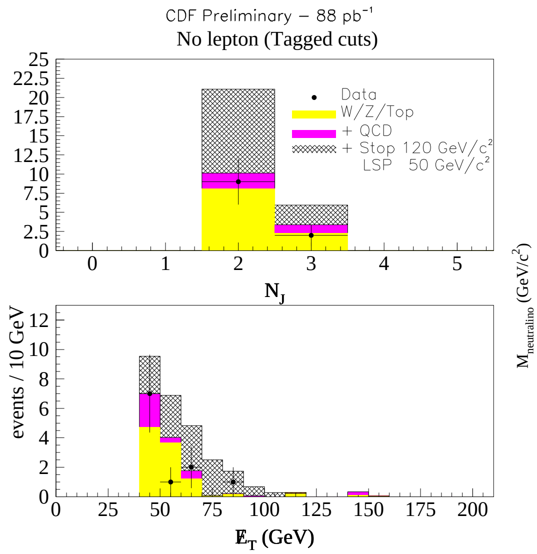

Figure 1: *Jet multiplicity and $\not\!\!E_T$ distribution after all cuts have been applied (CDF experiment).*

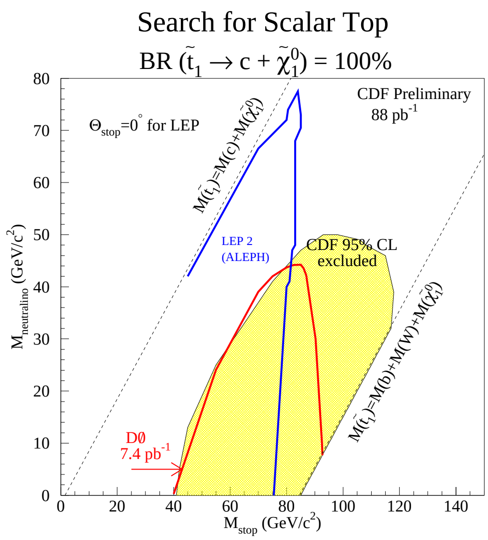

Figure 2: *95% C.L. limit as function of $M_{\tilde{\chi}_1^0}$ and $M_{\tilde{t}_1}$, for direct $\bar{\tilde{t}}_1\tilde{t}_1$ production, assuming $\mathcal{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 100\%$ (CDF experiment).*

which contains heavy non-Standard-Model particles. This sector then couples to a set of particles with Standard Model interactions, called messengers, which have a mass of order M. The mass splitting, between the superpartners in the messenger multiplets, depends by $\sqrt{F}$ and the SUSY particles get their masses via gauge interactions, so there are no flavor changing neutral currents. These theories have a very distinctive phenomenological features. The typical SUSY spectra is different from those in the SUGRA models; the LSP is the gravitino $\tilde{G}$ (in SUGRA $M_{\tilde{G}} \sim 1$ TeV), the next lightest supersymmetric particle (NLSP) has a lifetime that can vary strongly from model to model ($1\mu < c\tau <$ several Km) and decays into $\tilde{G}$.

2 Search for scalar top

Search for scalar top is particularly interesting since, in many SUSY models, the top-squark eigenstate $\tilde{t}_1$ (stop) is expected to be the lightest squark [8]. The strong Yukawa coupling, between top/stop and Higgs fields, gives rise, in fact, to potentially large mixing effects and mass splitting. The CDF experiment has recently performed two different searches for scalar top: direct $\bar{\tilde{t}}_1\tilde{t}_1$ production, assuming a branching ratio $\mathcal{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) =$ 100%, and a search for supersymmetric decays of the top quark: $t \to \tilde{t}_1\tilde{\chi}_1^0$, with $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$.

2.1 Search for direct Stop pair production

Whether $\mathcal{R}$-parity is conserved or not, at Tevatron, stop quarks are produced in pairs via gg and $q\bar{q}$ fusion. The LO diagonal pair production cross section depends mainly on stop mass and very little on other SUSY parameters such as gluino mass,

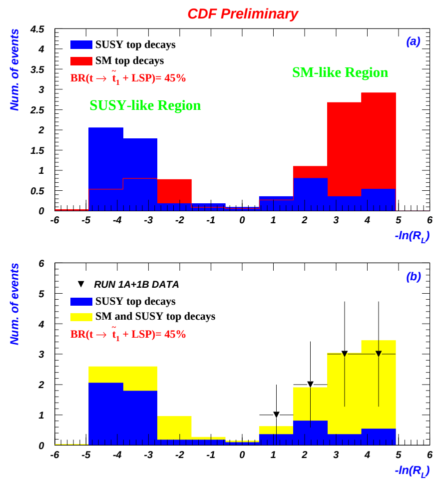

Figure 3: *a) Comparison of $-ln(R_{\mathcal{L}})$ for SM top decay and SUSY top decays after all the cuts have been applied. b) $-ln(R_{\mathcal{L}})$ distribution for Run 1 data (CDF experiment).*

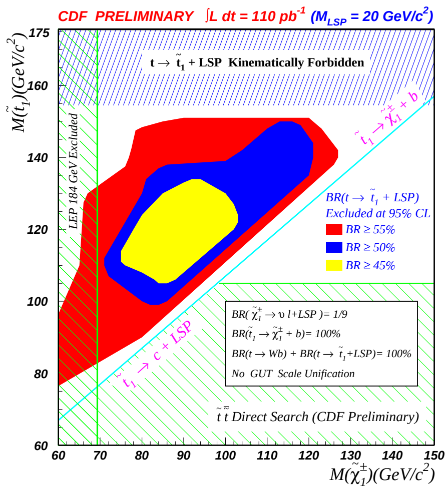

Figure 4: *95% C.L. excluded $\mathcal{BR}(t \rightarrow \tilde{t}_1 + \mathrm{LSP})$ as function of $m_{\tilde{\chi}_1^{\pm}}$ vs $m_{\tilde{t}_1}$, for $m_{\mathrm{LSP}} = 20$ GeV/c^2 (CDF experiment).*

the masses of the light flavor squarks and the mixing angle [9]. Whenever kinematically allowed, stop decays into $b\tilde{\chi}_1^{+}$; if this channel is closed, but sneutrino is light, then the decay $\tilde{t}_1 \rightarrow b\ell\tilde{\nu}$, dominates. When both these channels are kinematically suppressed, stop decays, via one-loop diagram, to charm neutralino ($\tilde{t} \rightarrow c\tilde{\chi}_1^0$). The signature for this process is two acollinear jets, coming from charmed quarks, a significant missing transverse energy contribution and no high-p_T leptons in the final state. The events have been selected requiring 2 or 3 jets having $E_T \geq 15$ GeV ($|\eta| \leq 2$) and $\not{E}_{\mathrm{T}} > 40\ GeV$. A lifetime tagging technique have been developed for c-quark identification. The probability, that an ensemble of tracks in a jet is consistent with being from the primary vertex, have been estimated; a probability of less than 5%, at least for one jet, have been required. The dominant background for this search comes from W/Z+jets, with an unidentified lepton (μ/e), produced in the W/Z boson decay, or from $W \rightarrow \tau\nu_\tau$, with τ decaying hadronically. We observe 11 events, when 14.5 ± 4.2 are expected from SM background (see figure 1). We therefore set a 95% Confidence Level (C.L.) limit as function of the $\tilde{t}_1$ and $\tilde{\chi}_1^0$ masses [10] (see figure 2).

2.2 Search for SUSY decays of the top

In the presence of a light stop, $M_{\tilde{t}_1} < M_t$, the top-quark could decay, with appreciable branching ratio, into stop plus neutralino: $t \rightarrow \tilde{t}_1\tilde{\chi}_1^0$, where $\tilde{\chi}_1^0$ is the LSP [11]. CDF has searched for such supersymmetric decays of the top, in the kinematic region where stop decays into chargino plus b-quark are dominant ($M_{\tilde{t}_1} > M_{\tilde{\chi}_1^{\pm}}$). The search has been performed on the full Run 1 data sample of $109.4 \pm 7.2\,\mathrm{pb}^{-1}$. The kinematic differences between SUSY and SM $t\bar{t}$ decays have been used to separate signal from background. A sample of $W+\geq 3$ jets top candidate events has been

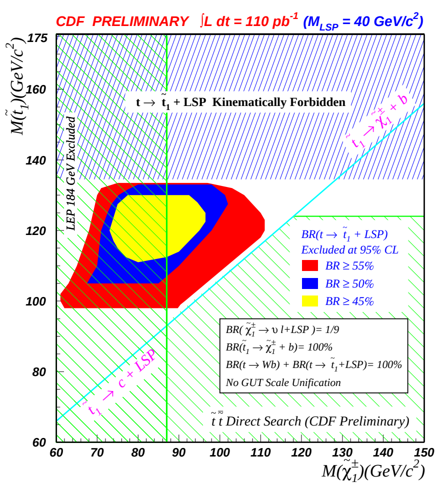

Figure 5: *95% C.L. excluded* $\mathcal{BR}(t \to \tilde{t}_1 + \mathrm{LSP})$ *as function of* $m_{\tilde{\chi}_1^{\pm}}$ *vs* $m_{\tilde{t}_1}$*, for* $m_{\mathrm{LSP}} = 40\ GeV/c^2$ *(CDF experiment).*

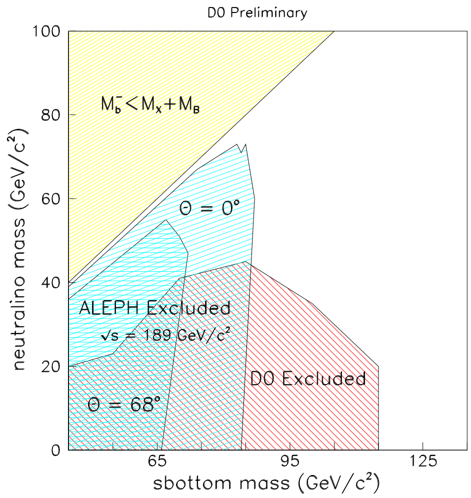

Figure 6: *95% C.L. excluded region in the* $M_{\tilde{b}_1}$*,* M_{LSP} *plane. The ALEPH contours correspond to* $\theta = 0°$ *and* $68°$ *(DØ detector).*

selected, from the inclusive lepton sample, by requiring: $E_{\mathrm{T}}^{e} > 20\ GeV/c^2$, $p_{\mathrm{T}}^{\mu} > 20\ GeV/c^2$, $\not{E}_{\mathrm{T}} > 25\ GeV$ and the mass of the transverse component of the lepton-$\not{E}_{\mathrm{T}}$ system (M_T) to be larger than 40 GeV. We required the presence of at least 3 jets: $E_T^{jet}(1) > 20\ GeV$, $E_T^{jet}(2) > 20\ GeV$, $E_T^{jet}(3) > 15\ GeV$ ($|\eta_{jet}| < 2$), satisfying the condition that the cosine of the angle, in the rest frame, between the proton beam and the jet (θ_i^*), have to be: $|cos(\theta_{\mathrm{i}}^*)|_1 < 0.9$, $|cos(\theta_{\mathrm{j}}^*)|_2 < 0.8$, $|cos(\theta_{\mathrm{k}}^*)|_3 < 0.7$, where $|cos(\theta_{\mathrm{j}}^*)|_{\mathrm{k}}$ are ordered quantities [12]. Further cuts have been applied to reduce QCD W+jets and SM top background, by requiring that the three highest jets are well separated, the reconstructed transverse momentum of the W is $p_T(W) > 50\ GeV/c$ and $\not{E}_{\mathrm{T}} > 45\ GeV$. Finally we required the presence of at least one b-jet by asking a SVX b-tag in the event. The discrimination between SUSY top decays and SM top background has been achieved by combining the information on the E_T^{jet} in a Relative Likelihood (see figure 3), defined as: $R_{\mathcal{L}} = \frac{\mathcal{L}_{Abs}^{SUSY}}{\mathcal{L}_{Abs}^{SM}}$, where $\mathcal{L}_{Abs}$ is the Absolute Likelihood function defined by the equation: $\mathcal{L}_{Abs} = \left(\frac{1}{\sigma}\frac{d\sigma}{dE_T^{jet}(2)}\right) \times \left(\frac{1}{\sigma}\frac{d\sigma}{dE_T^{jet}(3)}\right)$. Since no signal has been observed, we set a 95% $C.L.$ limit on $\mathcal{BR}(t \to \tilde{t}_1\tilde{\chi}_1^0)$, as function of $M_{\tilde{t}_1}$ and $M_{\tilde{\chi}_1^{\pm}}$, for M_{LSP} between 20 and 40 GeV/c^2 (see figure 4 and 5).

3 Search for scalar bottom

At large tanβ (tan$\beta > 10$)[13], a considerable $\tilde{b}_L - \tilde{b}_R$ mixing can occur in the sbottom sector, leading to a scenario in which the $\tilde{b}_1$ could be the lightest scalar quark. The LO and NLO diagonal pair production cross section are the same as for stop quark[9]. DØ has performed a search for light sbottom, assuming $\tilde{\chi}_1^0$ to be the LSP and fixing the branching ratio $\mathcal{BR}(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 100\%$. In the region of interest for the Teva-

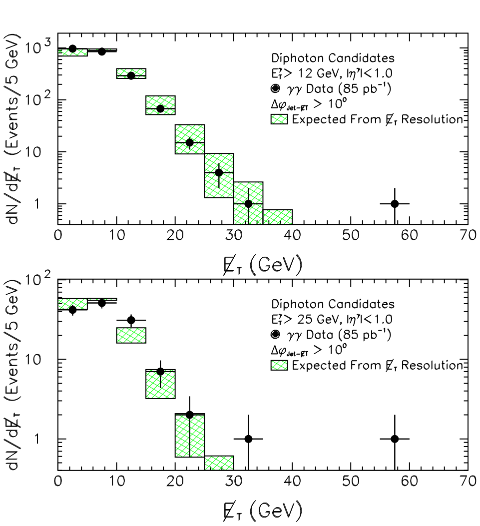

Figure 7: *The $\not{E}_T$ spectrum for diphoton events with $E_T^\gamma > 12\,GeV$ and with $E_T^\gamma > 25\,GeV$ in the data from CDF detector.*

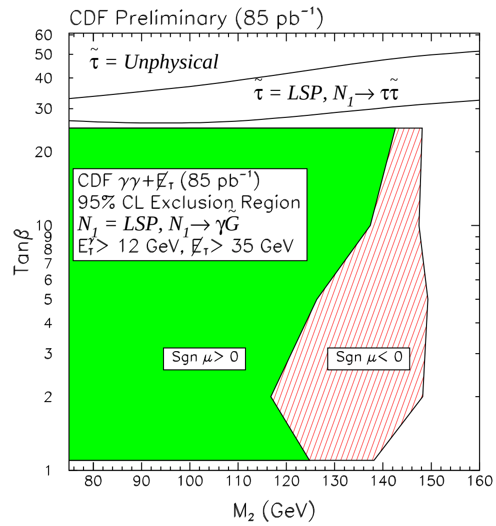

Figure 8: *95% C.L. excluded region (M_2 vs $\tan\beta$) for the Light Gravitino LSP scenario (CDF experiment).*

tron, the sbottom can only decay into $b\tilde{\chi}_1^0$. The decays of the sbottom into $\tilde{t}_1 W$, with a virtual W, $t\tilde{\chi}_1^-$, or into $\tilde{t}_1 H^\pm$ are kinematically suppressed. The signature for the process under study is therefore 2 b-quarks plus $\not{E}_T$. This final state is similar to those of two published DØ analysis: the search for third generation leptoquark ($\nu\nu bb$) [15], and the search for direct scalar top production ($\bar{\tilde{t}}_1\tilde{t}_1 \to c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$) [14]. The limits on sbottom production have been obtained combining these two samples. The number of events observed in the data is 5; 6.0 ± 1.3 events are expected from SM background. Figure 6 plots the 95% C.L. limit, as function of $M_{\tilde{b}_1}$ and $M_{\tilde{\chi}_1^0}$. A lower limit on the sbottom mass of $M_{\tilde{b}} > 115\ GeV/c^2$ which is valid for $M_{\tilde{\chi}_1^0} < 20\ GeV/c^2$ has been placed.

4 Photon enriched SUSY

In the last few years, triggered by the CDF $ee\gamma\gamma+\not{E}_T$ event candidate [16], many models of new physics, predicting photon enriched final states have been introduced. CDF and DØ have systematically searched for events containing two photons in the final state: $\gamma\gamma + X$, where X can be a jet, a b-tag, a lepton (e, μ, τ) or $\not{E}_T$.

4.1 Light Gravitino LSP

In the Minimal Gauge Mediated SUSY Breaking Model (MGM), as in SUGRA, the supersymmetry breaking occurs in a hidden sector. Unlike the SUGRA models, in which $\Lambda_{SUSY} \sim 10^{11}$, in MGM $\Lambda_{SUSY} \sim 10^5 - 10^9$, making the Gravitino the lightest supersymmetric particle ($M_{\tilde{G}} \sim 1 \div 10^2 eV$). The Next-to-lightest SUSY

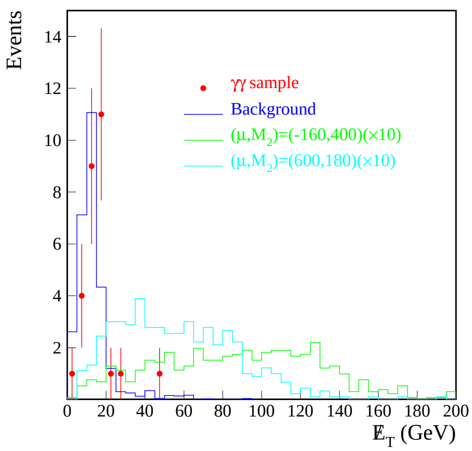

Figure 9: *The* $\not\!\!E_{\rm T}$ *spectrum for diphoton events with* $E_T^\gamma(1) > 20\,GeV$ *and* $E_T^\gamma(2) > 12\,GeV$ *in the data from DØ experiment.*

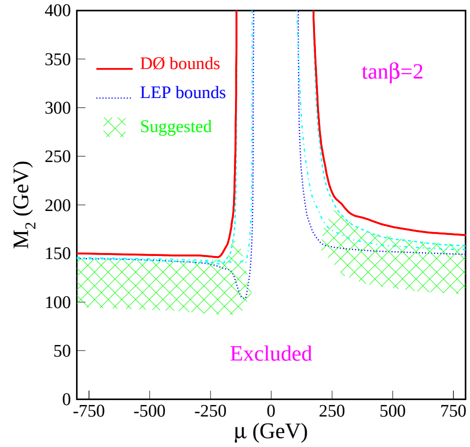

Figure 10: *95% C.L. excluded region (μ vs M_2) for the Light Gravitino LSP scenario (DØ detector); the dashed area shows the region suggested to explain the CDF* $ee\gamma\gamma+\not\!\!E_{\rm T}$ *event.*

particle (NLSP), which in the models is the neutralino ($\tilde\chi_1^0$), will decay dominantly via $\tilde\chi_1^0 \to \gamma\tilde G$. Therefore, any pair produced sparticle will produce two photons and $\not\!\!E_{\rm T}$ [17]. In this model the $\tilde\chi_1^0$ lifetime depends on $M_{\tilde G}$ and is assumed to be less than 1 KeV. The gaugino masses are defined by M_2, tanβ and signμ and $M_{\tilde\chi_1^\pm} \sim M_{\tilde\chi_1^0} \sim M_2$. In order to set a limit in this MGM model, the results of the counting experiment in the $\gamma\gamma\ \not\!\!E_{\rm T}$ have been used. Events are asked to have 2 photons with $E_T^\gamma > 12\ GeV$ ($|\eta| < 1$) and $\not\!\!E_{\rm T} > 35$ or $E_T^\gamma > 25\ GeV$ ($|\eta| < 1$) and $\not\!\!E_{\rm T} > 25$. For $\not\!\!E_{\rm T} > 35\ GeV$, 1 event passes the cuts, when the expected background is 0.5 ± 0.1 (see figure 7) [16]. Figure 8 shows the contour plot of the 95% C.L. excluded region as function of tanβ and M_2.
An analogous search has been performed by DØ Collaboration by selecting events with $E_T^{\gamma 1} > 20\ GeV$ and $E_T^{\gamma 2} > 12\ GeV$ ($|\eta| < 1.2$ or $1.5 < |\eta| < 2.0$). For $\not\!\!E_{\rm T} > 25\ GeV$, 2 events are observed when 2.3 ± 0.9 are expected from SM background processes (see figure 9). Figure 10 plots the 95% C.L. excluded region (μ vs M_2).

4.2 Neutralino Radiative Decay

The $\gamma\ \not\!\!E_{\rm T} + n$ jets event topology may also arise in MSSM, in some region of the parameter space, where the radiative decay $\tilde\chi_2^0 \to \gamma\tilde\chi_1^0$ dominates. Depending on the number of $\tilde\chi_2^0$, involved in the process, it will be possible to have one or more γ in the final state. DØ has searched for such signal using 99 pb^{-1} of data, assuming that slepton masses are heavy, $M_{\tilde\chi_2^0} - M_{\tilde\chi_1^0} > 20\ GeV/c^2$ and $\mathcal{BR}(\tilde\chi_2^0 \to \gamma\tilde\chi_1^0) = 100\%$. In order to select $\gamma\ \not\!\!E_{\rm T} + \geq 2$ jets event candidates, we require to have at least one identified photon with $E_T^\gamma > 20\ GeV, \not\!\!E_{\rm T} > 25\ GeV$ (see fig. 11) and two or more jets ($E_T^{jet} > 20\ GeV$). Then the event selection has been optimized in the $\not\!\!E_{\rm T}$, H_T plane ($\not\!\!E_{\rm T} > 45\ GeV$, $H_T > 220\ GeV$), resulting in 5 events passing the above cuts. 8.1 ± 5.8 events are expected from SM background processes. The 95% C.L. upper limit on $\sigma \times \mathcal{BR}$ as function of $M_{\tilde q}$ ($M_{\tilde q} = M_{\tilde g}$) is given in figure 12.

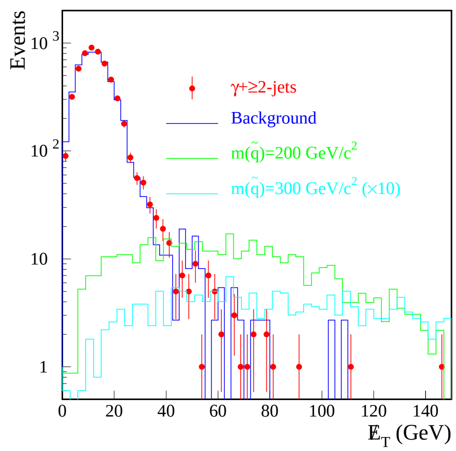

Figure 11: *The $\not\!\!E_T$ spectrum for events with one photon ($E_T^\gamma(1) > 20\,GeV$) and two or more jets ($E_T^{jet} > 20\,GeV$) in the data from DØ experiment.*

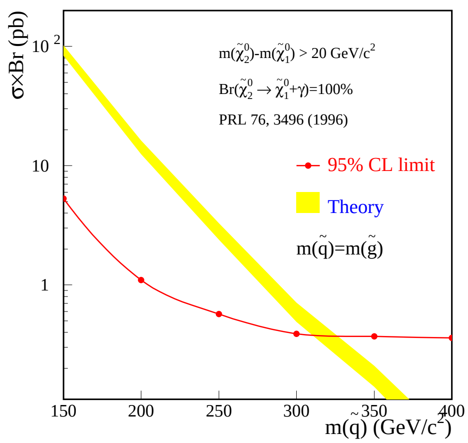

Figure 12: *The 95% C.L. upper limit on $\sigma\times\mathcal{BR}$ as function of $M_{\tilde{q}} = M_{\tilde{g}}$. The hatched band represents the range of theoretical cross section for different sets of MSSM parameter values (DØ experiment).*

4.3 The Higgsino LSP scenario

The present Higgsino LSP scenario assumes MSSM without sfermion/scalar masses unification. $\tilde{\chi}_1^0$ is an Higgsino-like LSP (tan$\beta = 1.2$), and $\tilde{\chi}_2^0$ is photino-like ($M_1 = M_2$). So doing this model predicts a large branching ratio for the process $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ and a light stop. A branching ratio of $\mathcal{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 100\%$ is assumed. We end up with a topology containing γb+$\not\!\!E_T$ in the final state: $p\bar{p} \to C_1\ N_2 \to \tilde{t}\, b\, \gamma\, N_1 \to c\, b\, \gamma\, N_1\, N_1$. CDF has searched for such events requiring a photon with $E_T^\gamma > 25$ GeV, a SVX b-tag and $\not\!\!E_T > 25\ GeV$. To increase the sensitivity we then required the photon to be not opposite to the $\not\!\!E_T$, and $\not\!\!E_T > 40\ GeV$ (see figure 13). We see 2 events; this allows to rule out more than approximately 7 events of anomalous production. Figure 14 shows the limit, plotted as function of gluino mass. In figure 15 we present the limit on direct production of $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$.

4.4 Gauge-mediated SUSY with γb+$\not\!\!E_T$

Another way to produce the γb+$\not\!\!E_T$ signature comes from a GMSB model. In this model, the gravitino is light and becomes the LSP. The $\tilde{\chi}_1^0$ is an higgsino and may decay into either a gravitino and a photon ($\tilde{\chi}_1^0 \to \tilde{G}\gamma$) or into a gravitino and an Higgs boson ($\tilde{\chi}_1^0 \to \tilde{G}h$), with the Higgs decaying into $b\bar{b}$. Since we have two $\tilde{\chi}_1^0$ in each event this will give rise to a γb+ $\not\!\!E_T$ signature. The CDF limits obtained in this scenario are shown in figure 16.

5 Conclusions

Extensive searches of supersymmetric signals have been done at Tevatron Collider. No positive results have been found so far showing that the data are consistent with

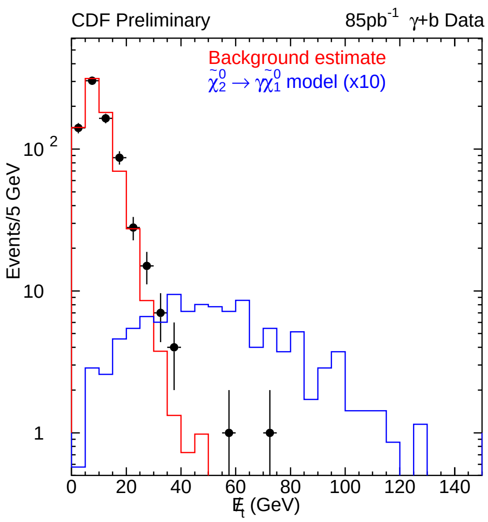

Figure 13: *The $\not{E}_T$ distribution in the data from CDF detector, compared to the SUSY Higgsino LSP baseline model.*

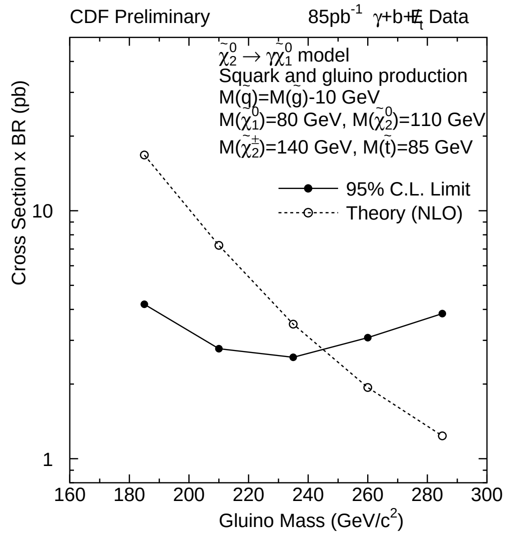

Figure 14: *The limits on the $\sigma \times \mathcal{BR}$ for SUSY production in the Higgsino LSP model (CDF experiment).*

the SM expectation. Further regions of SUSY parameter space, assuming different SUSY models, have been excluded. With the Run II [18] upgrades, providing an higher acceptance and higher luminosity, it will be possible to probe larger region of SUSY parameter space [19].

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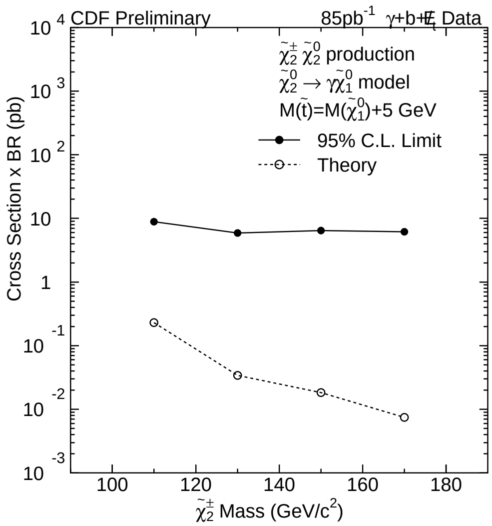

Figure 15: *The limits on the $\tilde{\chi}_2^{\pm}\tilde{\chi}_2^0$ cross section in the SUSY Higgsino LSP model (CDF experiment).*

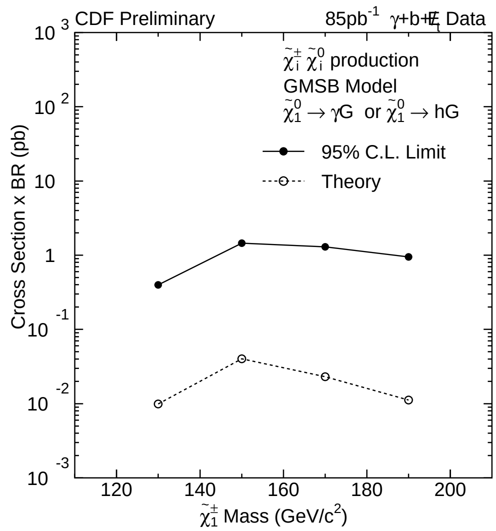

Figure 16: *The limits on the SUSY $\sigma \times \mathcal{BR}$ in the MGMSB model (CDF experiment).*

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